Fundamental Atomic Process in Source Development for Beyond EUV Lithography and “Water Window” imaging

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November 5, 2013

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ionization potential, transition probabilities. . .

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FAC/RATIP

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? CI effects
? Satellites

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CR model
CE model

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? Model development
? Validity condition
? Main contribution

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1-D Medusa
2-D Z^*

? DPP/LPP
? Wavelength/pulse
? Conversion efficiency
? Opacity
? Target geometry

Beyond 13.5 nm lithography (BEUVL)

nature photonics

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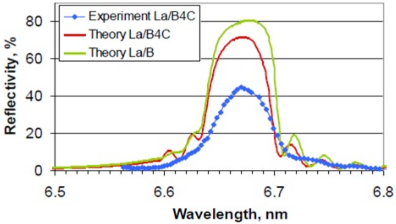
NATURE PHOTONICS | NEWS AND VIEWS

Optical lithography: Lithography at EUV wavelengths

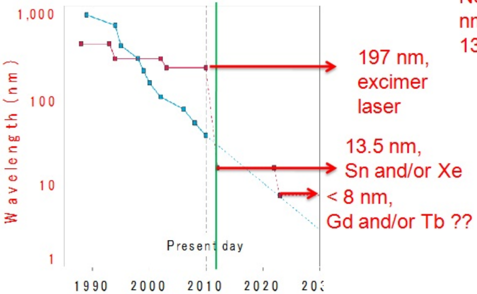
Greg Tallents, Erik Wagenaars & Geoff Pert

Affiliations

Nature Photonics **4**, 809–811 (2010) | doi:10.1038/nphoton.2010.277

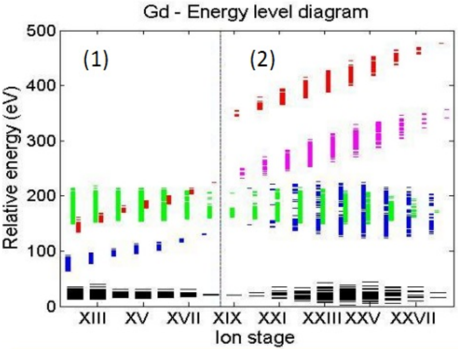


New sources would be needed at **6.x** nm for the future lithography beyond 13.5 nm.



*The precise value of **x** will be determined by the source and multilayer mirror combination that provides optimum efficiency and in-band EUV yield and its determination is a priority.*

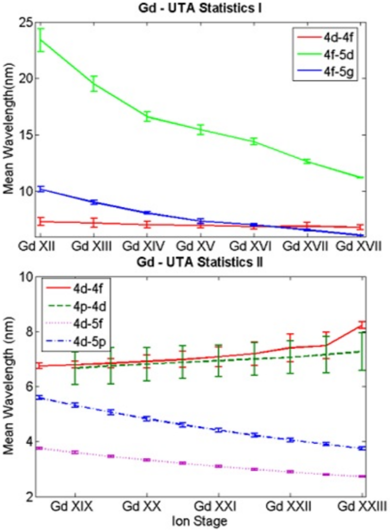
Energy levels and transitions of Gd



Energy-level diagram.

(1) Gd XII – Gd XVIII: 5d 4d^{-1} 5g and 4f.

(2) Gd XIX – Gd XXVIII: 4p^{-1} 4f 5f 5p and 4d



Most important ion stages ?

IOP Publishing — Journal of Physics B: Atomic, Molecular and Optical Physics

J. Phys. B: At. Mol. Opt. Phys. 43 (2010) 205004 (14pp) — doi:10.1088/0953-4075/43/20/205004

Tungsten spectra recorded at the LHD and comparison with calculations

C S Harte[1], C Suzuki[2], T Kato[2], H A Sakaue[2], D Kato[2], K Sato[2], N Tamura[2], S Sudo[2], R D'Arcy[1], E Sokell[1], J White[1] and G O'Sullivan[1]

[1] University College Dublin, Belfield, Dublin 4, Ireland
[2] National Institute for Fusion Science, 322-6 Oroshi-cho, Toki 509-5292, Japan

In all reported studies the emission is dominated by Ag and Pd-like lines i.e the spectra containing fewest lines where the emission is not divided amongst many transitions.

The most important transitions can be inferred from studies of W spectra.

They occur in Ag-like, Pd-like and Rh- like W^{27+}- W^{30+}. *Sugar et al JOSA 10, 1321 (1993)*

Gd XVIII-XX, Tb XIX - XXI

i.e. Ions with $4d^{10}4f$, $4d^{10}$ and $4d^9$ ground states

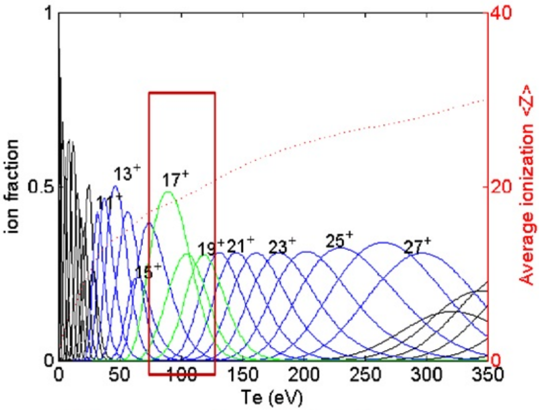
Power density required ?

Steady-state CR model

$$f_z = \frac{n_{z+1}}{n_z} = \frac{S(z)}{\alpha_r(z+1) + n_e\alpha_{3b}(z+1)}$$

n_z = density of ion z,
n_e = electron density,
S = collisional ionisation rate coefficient,
α_r = radiative recombination rate coefficient,
$n_e\alpha_{3b}$ = three-body recombination rate coefficients and T_e = electron temperature

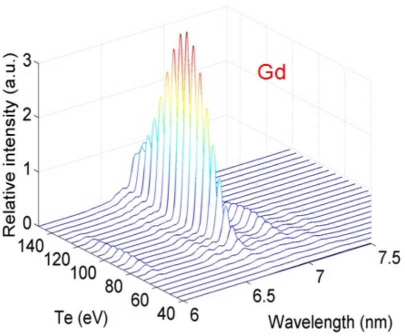
D. Colombant and G. F. Tonon, J. Appl. Phys. ***44*** *(1973) 3524*

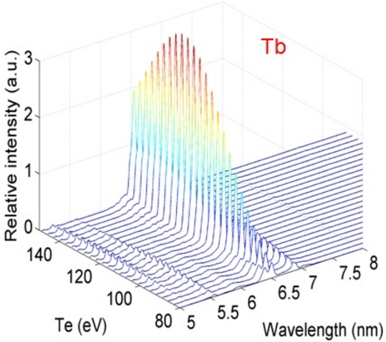


The laser power density required lies in the range
$2\times10^{12} - 10^{13}$ Wcm^{-2} @λ =1.06 μm
$2\times10^{11} - 10^{12}$ Wcm^{-2} @λ =10.6 μm

80 – 130 eV !!

The synthetic spectra





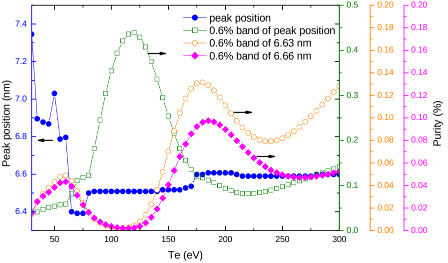
Gd: x=0.76, optimum temperature $\sim$ 110 eV
Tb: x=0.51, optimum temperature $\sim$ 120 eV

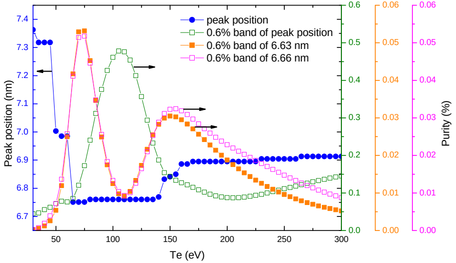
MLM @ 6.x nm

Perfect mirror:
LaN/B: maximum reflectance at 6.66 nm
LaN/B_4C: maximum reflectance at 6.63 nm

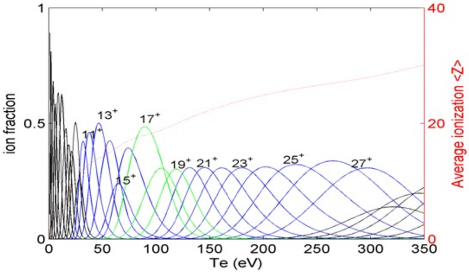
Position of peak emission and purity

Calculated position of peak emission from Tb (left) and Gd (right) spectra as a function of electron temperature. Plots of spectral purity as a function of electron temperature are also included for three 0.6% reflectivity bands: one centered at the wavelength of peak emission and the other two as indicated





Influence of dielectronic recombination



$$f_z = \frac{n_{z+1}}{n_z} = \frac{S(z)}{\alpha_r(z+1) + n_e\alpha_{3b}(z+1)}$$

n_z = density of ion z,
n_e = electron density,
S = collisional ionisation rate coefficient,
α_r = radiative recombination rate coefficient,
$n_e\alpha_{3b}$ = three-body recombination rate coefficients and T_e = electron temperature

PHYSICAL REVIEW A **83**, 062708 (2011)

Theoretical investigation of dielectronic recombination of Sn^{12+} ions

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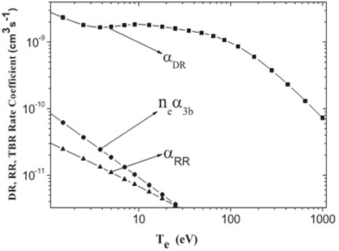
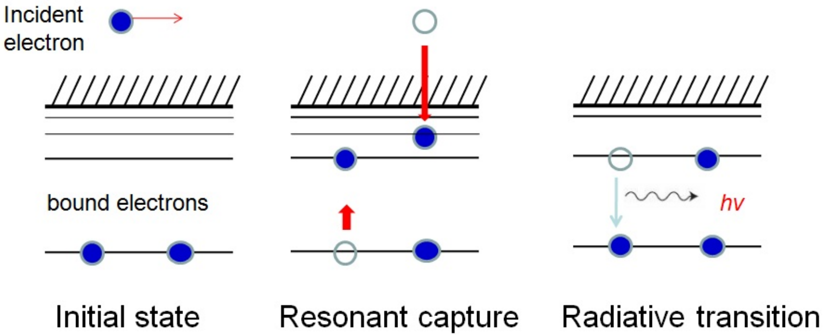
(Received 1 April 2011; published 21 June 2011)



What is DR process



$$e + A^{q+}(i) \rightarrow [A(q\text{-}1)+]^{**}(j) \rightarrow [A(q\text{-}1)+]^{*}(k) + hv$$

$$[\mathrm{Zn}]\, 4p^6 4d^9 + e \rightarrow [\mathrm{Zn}]\, 4p^6 4d^8 n'l' nl,\; n'l' = 4f, 5l, 6l,$$

$$+ 4p^5 4d^{10} nl + 4p^5 4d^9 n'l' nl,\; n'l' = 4f, 5l, 6l,$$

$$[\mathrm{Zn}]\, 4p^6 4d^8 n'l' nl + 4p^5 4d^{10} nl + 4p^5 4d^9 n'l' nl,$$

$$\rightarrow [\mathrm{Zn}]\, 4p^6 4d^9\, nl + 4p^6 4d^8\, n'l' n''l'' + h\nu,$$

$$\downarrow \qquad \textbf{RS} \qquad \textbf{NRS}$$

$$[\mathrm{Zn}]\, 4p^6 4d^9 + e$$

Calculation of DR

PHYSICAL REVIEW A **85**, 012712 (2012)

Dielectronic recombination of Pd-like gadolinium

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Joint Laboratory of Atomic and Molecular Physics, NWNU and IMP CAS, Lanzhou 730070, China

(Received 30 September 2011; revised manuscript received 16 December 2011; published 30 January 2012)

As research and development of extreme ultraviolet lithography (EUVL) sources at 6.7 nm (which will be based on emission from ionized gadolinium) has already begun, reliable atomic data are required in order to determine the optimum plasma conditions. However, the complexity of the atomic structure means that *ab initio* level-resolved dielectronic recombination (DR) calculations are currently unavailable for the ions of interest. Here we report the first detailed calculation of the DR rate coefficients for the ground state and first excited states of Pd-like gadolinium. Energy levels, radiative transition probabilities, and autoionization rates of Ag-like gadolinium for [Kr]$4d^9 4fnl$, [Kr]$4p^5 4d^{10} 4fnl$, [Kr]$4d^9 5l'nl$, and [Kr]$4d^9 6l'nl$ ($n \leqslant 18$) complexes were calculated using the flexible atomic code (FAC). It was found that inclusion of $4p^5 4d^{10} 4fnl$ configurations has significant influence on the total DR rate coefficient. The DR rate coefficients obtained here are compared with radiative recombination and three-body recombination coeffcients. The results show that the DR rate coefficient is almost an order of magnitude higher than the coefficients for the other two recombination processes combined at plasma electron temperatures around 110 eV, which suggests that the DR process should be included in theoretical modeling for Pd-like gadolinium in EUVL source plasmas.

PHYSICAL REVIEW A **85**, 052706 (2012)

Dielectronic recombination of Rh-like Gd and W

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Y. B. Fu and C. Z. Dong
Key Laboratory of Atomic and Molecular Physics & Functional Materials of Gansu Province,
College of Physics and Electronics Engineering, orthwest Normal University, Lanzhou 730070, China, and

Energy levels of Gd and W

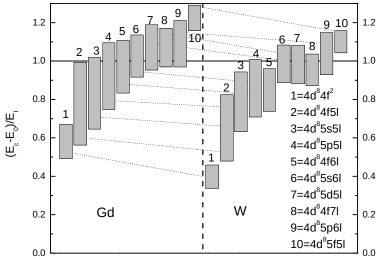


Figure : The energy levels near the ionization limits for 4d complexes

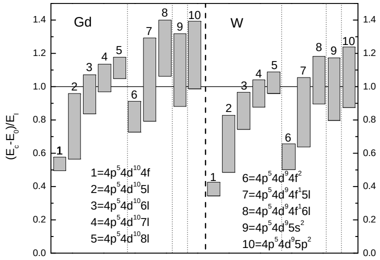


Figure : The energy levels near the ionization limits for 4p complexes

DR of Rh-like Gd and W

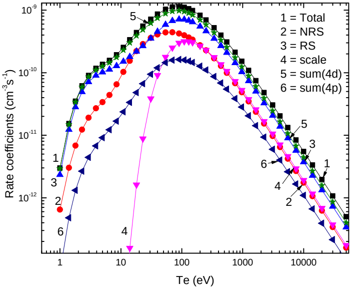


Figure : Gd

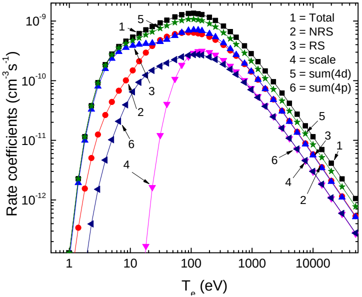
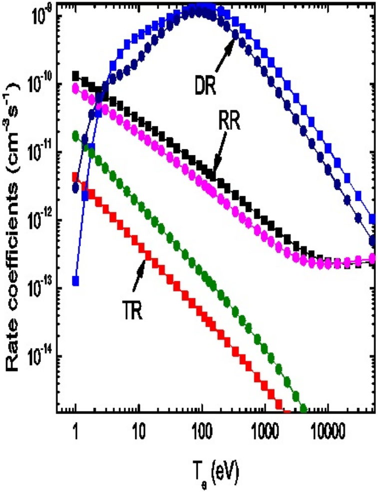


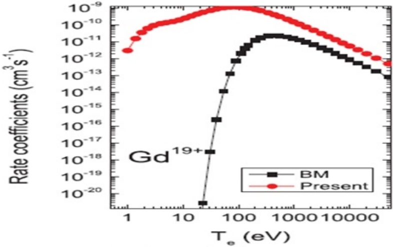
Figure : W

- The 4p complexes contribute around 25% to the total DR rate coefficients
- the contributions from NRS transitions are significantly enchanced for W when compared with Gd as a result of lowering of energy levels relative to the ionization limit

Influence of DR process



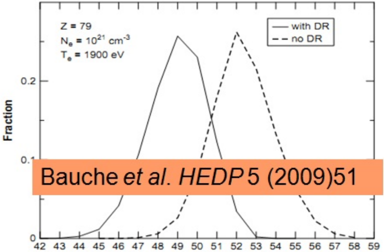
Gd (circles) and W (squares)



Burgess-Merts (BM) approximation

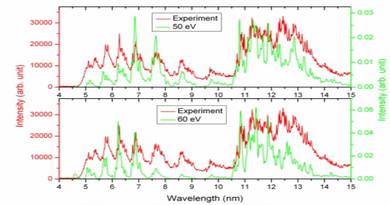
A. Burgess, Astrophys. J **141**, 1588 (1965).

A. Merts, R. D. Cowan, N. H. J. Magee, Los Almos Scientific Laboratory Report No. LA-6220-MS, 1976 (unpublished).

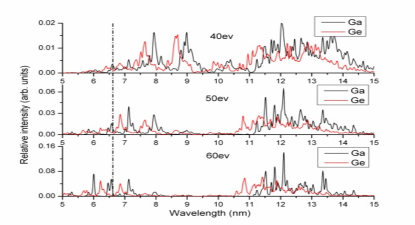


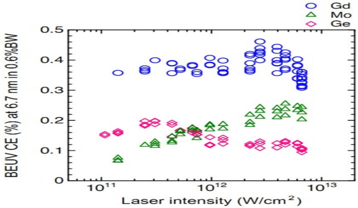
Bauche *et al. HEDP* 5 (2009)51

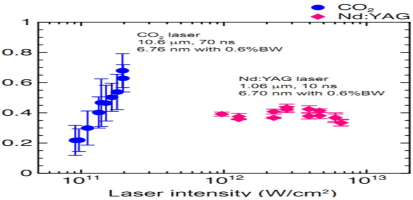
Future work: Ga/Ge?



Experiment: Taka







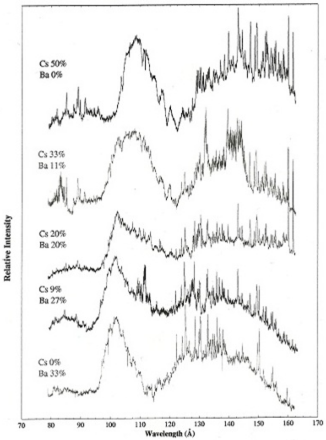
Experiment: Prof. T. Higashiguchi

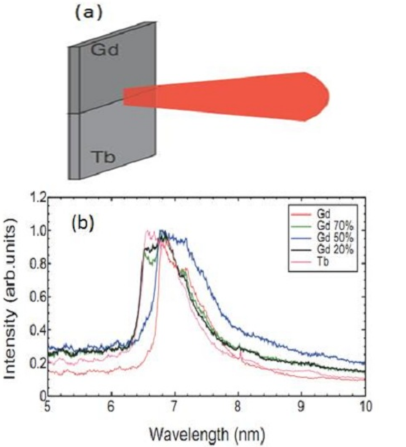
Galinstan deserve a detailed study:

1)low melting temperature

2)current Laser assisted DPP can be directly transferred

Future work: Complex target?



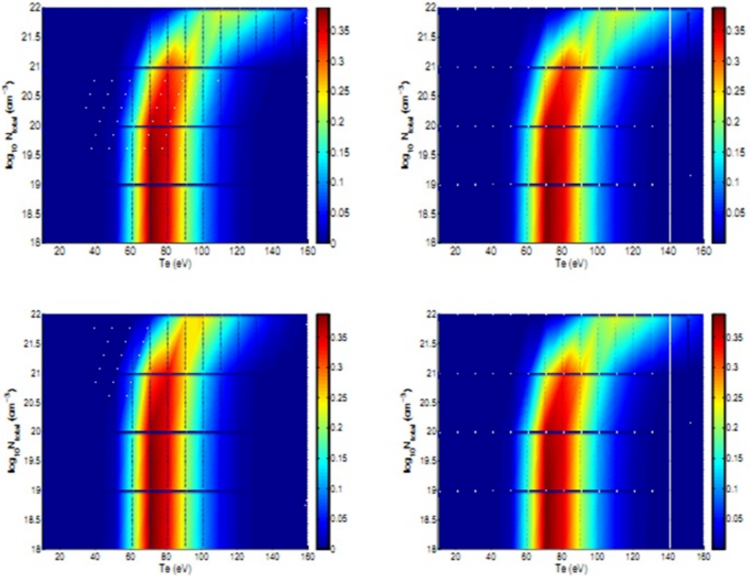


Experiment: T. Faulkner

Experiment: Takeshi Higashiguchi

Complex target by using nano-particles or colliding plasma might be a solution!

Ionic fraction for complex target



Section conclusions

- The emission processes in Gd/Tb is more efficient than in Sn because the 4f wavefunction is completely contracted in the relevant ions. Strongest lines are expected from Ag-, Pd- and Rh-like ions.
- Gd: x=0.76, optimum temperature $\sim$ 110 eV.
- Tb: x=0.51, optimum temperature $\sim$ 120 eV.
- Dielectronic recombination process is important.
- Future work:
  modelling plasma hydrodynamics and radiation transport, to find both the optimum temperature and source conditions.

WW soft x-ray source

Water Window: 2.3–4.4 nm. In this region, the absorption of carbon is approximately 10 times higher than that of oxygen and water.

Potential Commercial Uses: x-ray microscopy, absorption spectroscopy, etc.

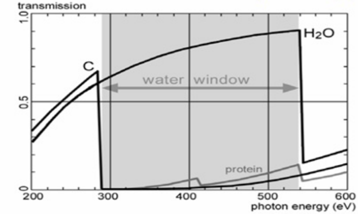


Fig.1. "Water window" X-ray energy range.

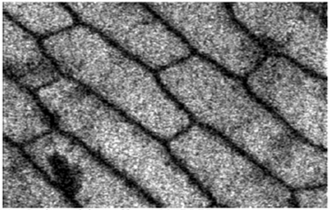
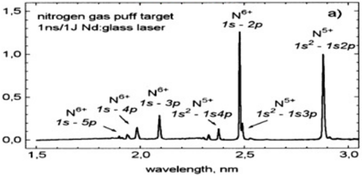


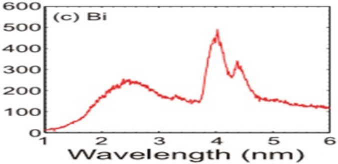
Fig.2. Onion skin cells, 450eV X-ray energy, 800nm pixel size.

A. Sasov X-ray microscopy of living cells 5th IEEE international symposium on biomedical imaging

Line source

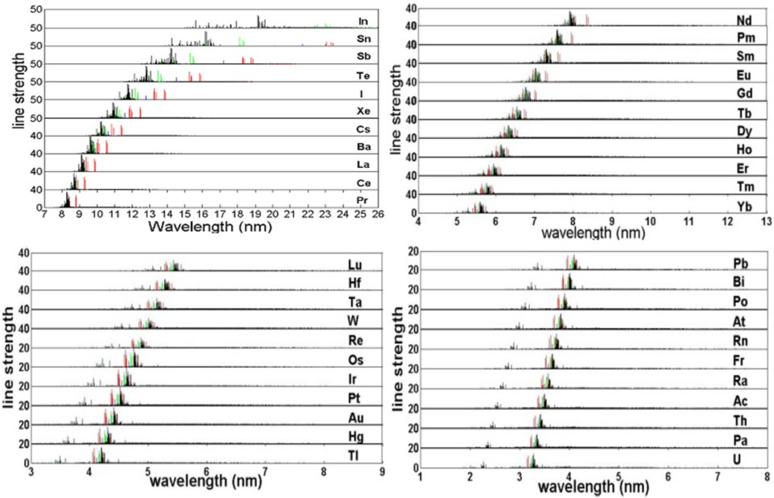


Continuum source



Proposed by Prof. O'Sullivan & Prof. Endo

Variation of UTA vs Z



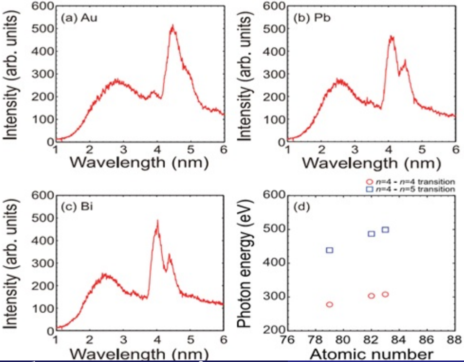
Bowen Li et al. Proc. SPIE 8139 (2011) 81390P

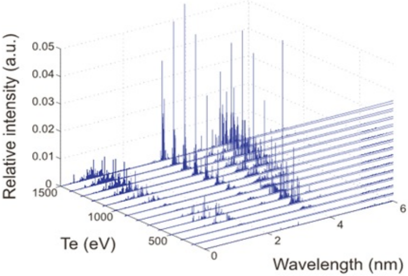
Bi as a choice ($\Delta n = 0$)

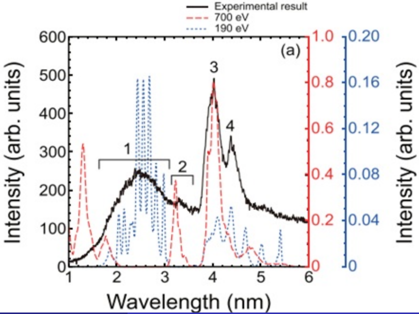
APPLIED PHYSICS LETTERS 100, 014103 (2012)

Feasibility study of broadband efficient "water window" source

Takeshi Higashiguchi,[1,2,a)] Takamitsu Otsuka,[1] Noboru Yugami,[1,2] Weihua Jiang,[3] Akira Endo,[4] Bowen Li,[5] Padraig Dunne,[5] and Gerry O'Sullivan[5]
[1]Department of Advanced Interdisciplinary Sciences, Center for Optical Research & Education (CORE), and Optical Technology Innovation Center (OpTIC), Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585, Japan
[2]Japan Science and Technology Agency, CREST, 4-1-8 Honcho, Kanagawa, Saitama 332-0012, Japan
[3]Department of Electrical Engineering, Nagaoka University of Technology, Kami-tomiokamachi 1603-1, Nagaoka, Niigata 940-2188, Japan
[4]Research Institute for Science and Engineering, Waseda University, Okubo 3-4-1, Shinjuku, Tokyo 169-8555, Japan
[5]School of Physics, University College Dublin, Belfield, Dublin 4, Ireland







Zr as a choice ($\Delta n = 1$)

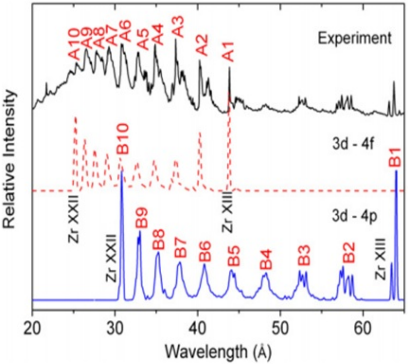


Figure 1. Comparison of the experimental spectrum of Zr with theoretical resonance transitions. 3d–4f and 3d–4p transitions are clearly seen for each ion with a $3d^n$ ground configuration.

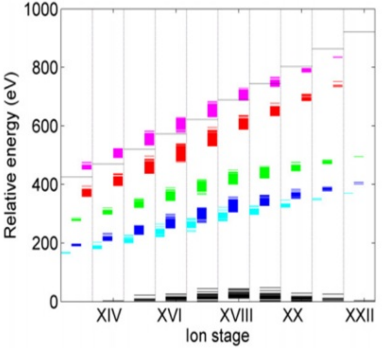
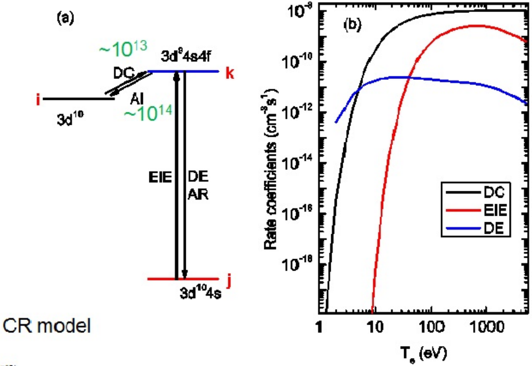


Figure 2. Energy-level diagram showing the level structure of $3d^n$, $3d^{n-1}$ (4s, 4p, 4f) and $3d^{n-2}$ 4s (4p, 4f) configurations for each ion stage in ascending order. The ionization limit is indicated by the long solid line.

Spectator transition: $3d^{n-1}4s - 3d^{n-2}4s4f$

Bowen Li, et al., J. Phys. B **45**, 245004 (2012)

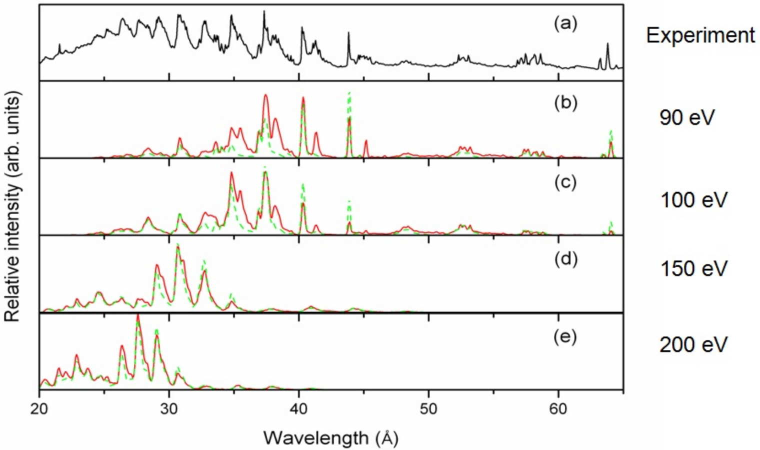


$$\frac{dN(k)}{dt} = R^{DC}(i)N_e N(i) + R^{EIE}(j,k)N_e N(j) - (R^{DE}(k,j)N_e + A^r(k,j) + A^a(k,i))N(k)$$

$$= 0$$

DC – Dielectronic capture; AI – Autoionization; EIE – Electron impact excitation; DE – De-excitation; AR – Radiative transition

Spectator satellite transition is important!



Cyan lines: Without satellite lines
Red line: With satellite lines

Influence of bandwidths and power densities

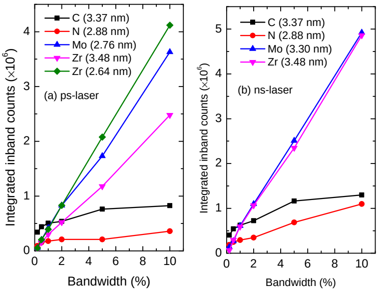


Figure : Variation in total counts as a function of multilayer reflective bandwidth for water window emission from 150-ps (a) and 10-ns (b) laser-produced plasmas of Zr

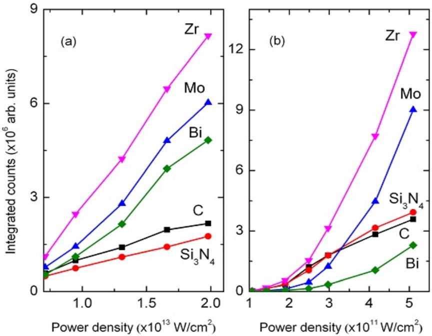


Figure : Water window emission (total counts) as a function of power density for 150 ps (a) and 10 ns (b) laser pulses

Further work

Emission properties of ns and ps laser-induced soft x-ray sources using pulsed gas jets

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lengths. Li et al. [35] observed a similar shift to shorter wavelengths with increasing pulse energy using a 150 ps Nd:YAG laser for plasmas induced on a solid state zirconium target.

On the other hand, Li et al. note higher total emission intensities for ns laser-induced plasmas of Zr, Mo, C and N from solid targets compared to ps laser plasmas.

Section conclusions

- We have demonstrated a laser-produced plasma soft x-ray source in the water window spectral region using high-Z plasmas, like a Bi plasma as a water window source for biological microscopy.
- $\triangle$n $=1$ transitions, like Zr, might be useful with narrow bandwidth reflector for water window source.
- Dielectronic recombination satellite lines is important.

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